Dynamic Characterisation of Additively Manufactured Honeycomb Architectures for Enhanced Energy Dissipation

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Possible Sessions
16. Novel Experimental Techniques, 23. Testing of Additive Materials, 26. Testing of Polymers

Introduction

Honeycomb lattice structures manufactured via stereolithography (SLA) using a flexible polymer resin have been investigated for their energy dissipative capabilities under a broad range of compressive strain rates. The architectures employ honeycomb-based unit cells to introduce anisotropic compressive behaviour through varied modes of geometrical collapse. Such structures are of interest for impact mitigation in diverse applications including sports helmets and pads, automotive crash protection systems, and protective wearable technologies for medical and industrial use due to their low density, high deformability, and superior energy dissipation compared to conventional rigid foams. The introduced anisotropy provides improved versatility, especially under multidirectional loading, making them particularly effective in scenarios involving unpredictable or off-axis impacts. This study aims to characterise the mechanical response of these flexible honeycomb lattices across a wide range of loading regimes (10^{-3} – 10^{3} s^{-1}), assess their energy absorption relative to a widely used rigid polymer foam (Rohacell® 71) [1], and establish a validated finite element model to support iterative design optimisation for targeted performance outcomes.

Methodology

Additive Manufacturing. The structures presented in this study were fabricated using stereolithography (SLA), a vat photopolymerisation technique. All test specimens were produced using a Form 3L printer (Formlabs®) with urethane-based flexible resin. The unit cell design is based on a honeycomb pillar geometry with variations in the midsection geometry. The ‘Egg-box’ design in Fig.1 b) was intended to induce controlled collapse under axial loading while providing increased lateral stiffness under transverse compression. This multi-mode behaviour, in combination with the chosen material, contributed to improved resilience and reusability under repeated loading cycles.

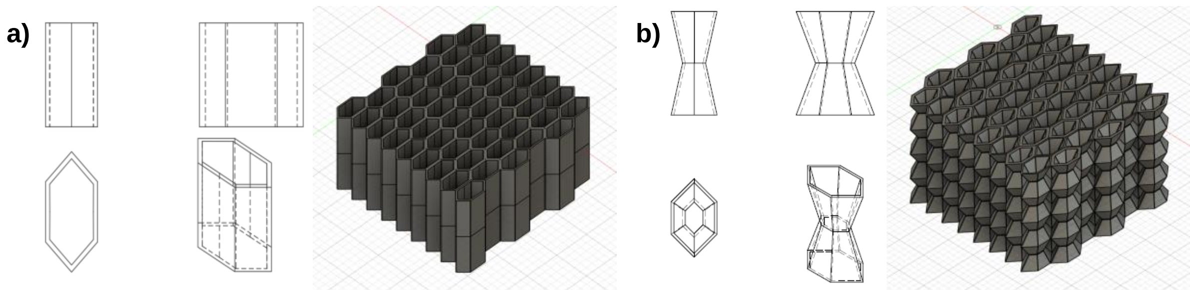

Figure 1. Honeycomb based architectures considered in the study: a) straight column ‘Pillar’ architecture and b) concave column 'Egg-box' structure.

Experimental Methods. Compression tests were performed on the fabricated lattice specimens across several decades of strain rate. Quasi-static tests (~10^{-3} s^{-1}) were conducted using a universal testing machine, while intermediate strain-rate tests (~1–10 s^{-1}) were carried out using a servo-hydraulic apparatus. For high strain-rate loading in the ~10^{3} s^{-1} regime, a modified Direct Impact Hopkinson Pressure Bar (mDIHPB) technique was developed and employed (Fig. 2) [2]. This novel set-up was specifically designed to enable high-rate compression testing of low-impedance materials, offering enhanced force sensitivity and improved temporal resolution. It addresses several limitations inherent to conventional diagnostics such as the Split Hopkinson Pressure Bar (SHPB) and drop-weight methods, including poor signal transmission, high noise levels and insufficient time resolution to observe post-densification behaviour [3]. High-speed imaging was utilised during the impact tests to enable near-field visualisation of deformation mechanisms and to validate strain measurements. The energy dissipation capacity of the structures was quantified by integrating the stress–strain response to calculate the energy dissipated per unit volume ($J{\cdot}m^{-3}$), as well as by determining the specific energy dissipation ($J{\cdot}kg^{-1}$) for each structure. The two distinct honeycomb-based lattice structures differing in unit cell geometry, were assessed to explore how architectural variations influence mechanical response and energy dissipation capabilities. For comparative purposes, a rigid closed cell polymethacrylimide (PMI) foam (Rohacell® 71), widely used in lightweight sandwich core applications, was tested under identical loading conditions to establish a baseline for performance evaluation. All three materials were compared in terms of key performance metrics, including energy dissipation capacity and deformation behaviour, across the full range of applied strain rates. This comparative approach provides insight into the relative advantages of architected flexible lattices over conventional foam materials for impact mitigation applications.

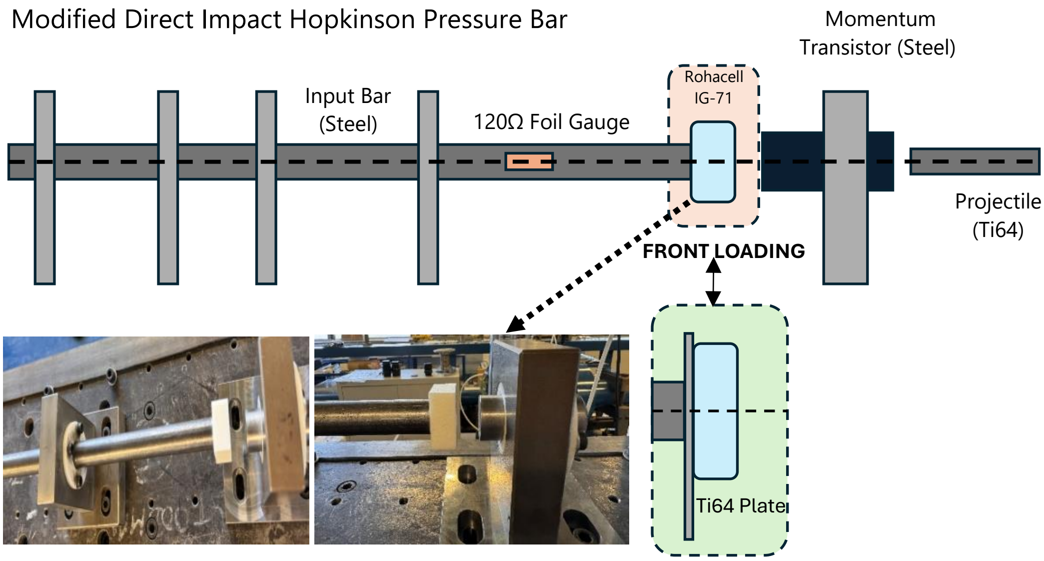

Figure 2. Schematic of the modified DIHPB system used for high-rate compression testing at the Impact and Shock Mechanics Group, University of Oxford.

Numerical Modelling. Numerical simulations are proposed to assess current modelling techniques and support the design of additively manufactured (AM) lattice structures. A finite element modelling (FEM) framework complements experimental investigations, incorporating a constitutive model for the SLA polymer resin, characterised as a non-linear viscoelastic material using strain-rate-dependent uniaxial test data. A combined hyperelastic-viscoelastic formulation captures both elastic and time-dependent viscous behaviour, particularly under high strain rates. The simulations span quasi-static and high-rate regimes, including a validated digital twin of the mDIHPB setup to ensure realistic boundary conditions. These models enable validation of experimental results and facilitate the development of predictive tools to identify optimised structural configurations for target mechanical responses.

Conclusion

This study outlines a methodology for evaluating SLA-fabricated flexible honeycomb lattice structures designed for energy dissipation across a wide range of strain rates. Central to this approach is a modified Direct Impact Hopkinson Pressure Bar (mDIHPB), enabling improved high-rate testing of soft, anisotropic lattices. Alongside this, a finite element modelling framework has been developed, incorporating viscoelastic material behaviour to simulate and validate both quasi-static and dynamic responses. Together, these methods support iterative optimisation of the lattice geometry, offering a pathway towards the development of tunable, high-performance impact-mitigating structures.

References

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